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Toyota's New Combustion Technology for High Engine Thermal Efficiency and High Engine Output Performance

Toyotas neue Verbrennungstechnik für hohen thermischen Wirkungsgrad und hohe Motorleistung

Abstract

Currently, it is mandatory to improve vehicle fuel economy to respect energy security and climate change. To meet these requirements, Toyota has been developing new technologies called ESTEC (Economy with Superior Thermal Efficient Combustion) for enhancing engine thermal efficiency [1-3]. In addition to improving the vehicle fuel economy, Toyota considers enhancing the engine output performance that is important to realize "Fun to Drive" for customer's smile.

As for the engine development, it is also essential to consider the world situation such as air environment and a sales area. In terms of sales area, a vehicle sales volume in Asia is growing which means that car manufactures need to develop various types of vehicles and engines for worldwide customers. However, it takes a lot of efforts to develop several types of engines with high thermal efficiency and enhanced performance for worldwide market.

Therefore, Toyota is challenging to build up a new common architecture concept to effectively develop new generation engines. Since building up a new common architecture concept leads to develop new engines effectively, Toyota is considering enhancing value of product by making use of yielded time with efficient engine developments.

This paper presents some physical quantities, such as airflow, air turbulence intensity and tumble ratio which determine combustion characteristics and in-cylinder charging-air amount. Then the direction of the common architecture concept is discussed by using the relationship between the physical quantities and the engine design such as stroke-bore ratio, intake port design, and valve-train system. Toyota is pushing the development for the next generation engines which have not only high thermal efficiency but also high output performance.

Kurzfassung

Um die Herausforderungen der Energieversorgung und des Klimawandels zu meistern, ist es unbedingt erforderlich, den Kraftstoffverbrauch der Fahrzeuge zu senken. Hierzu hat Toyota Technologien unter dem Projektnamen ESTEC (Economy with Superior Thermal Efficient Combustion) entwickelt, um den thermischen Wirkungsgrad zu verbessern [1-3]. Zudem ist verbesserte Motorleistung wichtig für "Fun to Drive" als ein Beitrag zu höchster Kundenzufriedenheit.

In der Motorenentwicklung muss die Situation global betrachtet werden und das Potential für Luftqualität und regionale sowie globale Märkte einschliessen. Stetig wachsende Märkte wie z.B. der asiatische veranlassen die Hersteller neue Fahrzeugmodelle und

Motoren zu entwickeln. Der Aufwand, mehrere neue Fahrzeug- und Motorentypen mit hohem Wirkungsgrad und Leistung für den globalen Markt zu entwickeln, ist jedoch enorm. Toyota entwickelt daher eine neues Konzept einer gemeinsamen Architektur, um effizient eine neue Motorengeneration zu entwickeln. Dies erlaubt wiederum erhöhtes Augenmerk auf weitere Produktwerte.

Luftmasse und Turbulenz sowie Tumble sind entscheidende Characteristika für die Verbrennung und Verbrennungsluft im Zylinder. Mit diesen physikalischen Werten und dem Zusammenhang mit der Motorenkonstruktion wie z.B. Hub-Bohrungsverhältnis, Einlasskanalauslegung und Ventiltrieb wurde die neue Architektur festgelegt. Mit diesem Konzept entwickelt Toyota eine neue Motorengeneration mit hohem thermischen Wirkungsgrad und hoher Leistung..

Introduction

Toyota has been focusing on enhancing engine thermal efficiency to meet the social requirements and to overcome environmental issues such as energy security, climate change and air pollution. Figure 1 shows the history of the engine thermal efficiency and the future direction for reducing CO_2 [4,5]. In addition to enhancing the engine thermal efficiency, "Fun to Drive" is an important factor for supplying attractive vehicles. Figure 2 shows the trade-off between the maximum engine thermal efficiency and the maximum engine specific output. To overcome the trade-off, key technologies are intake port design, valvetrain system, and anti-knock quality in engine developments. Toyota is developing new technologies for realizing the future trend in Figure 2.

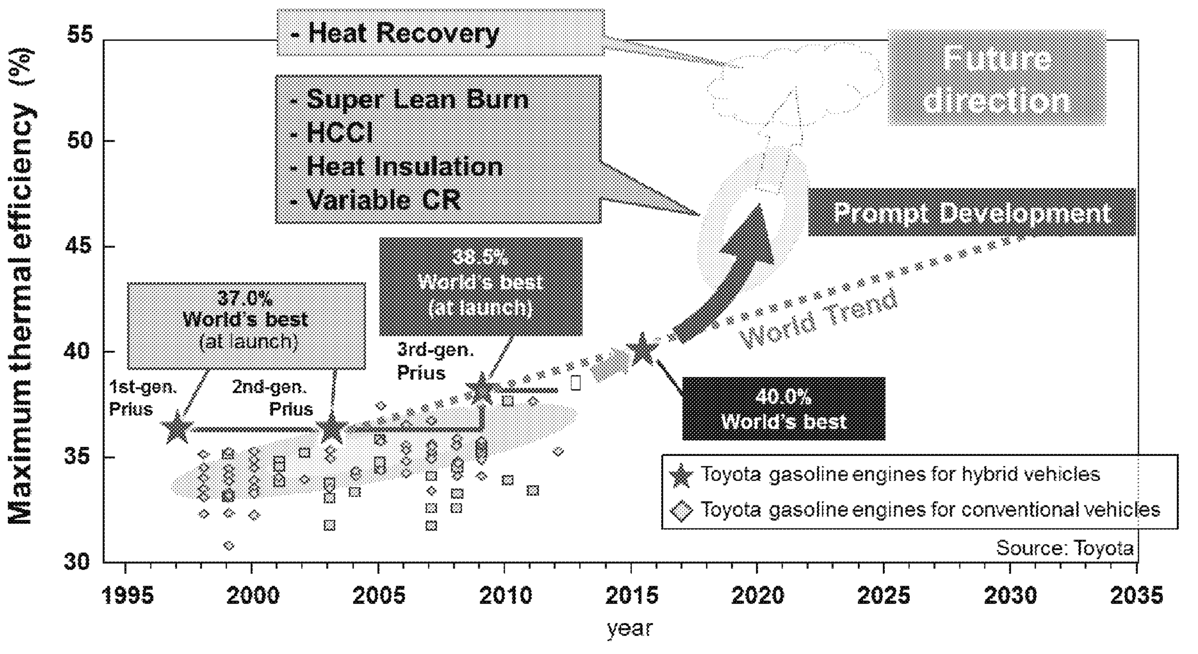

Figure 1. History of maximum engine thermal efficiency and future direction

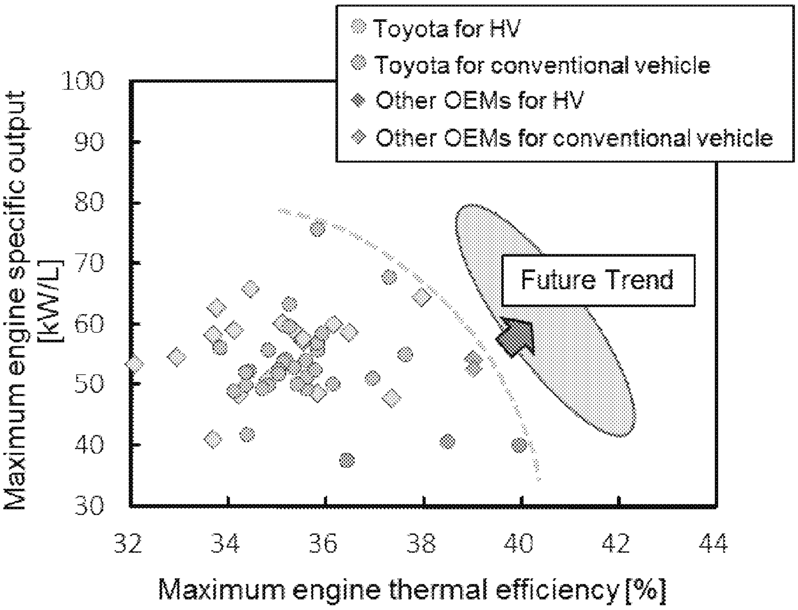

Figure 2. Trade-off between maximum engine thermal efficiency and maximum engine specific output and future trend

In terms of the engine development, selling countries and sales volume should be considered, because the customer's demand change from country to country. Figure 3 shows one example of sales volume change in Europe, U.S.A., Japan, China and BRICs. It shows that emerging countries are becoming important markets for car manufacturers. It means that car manufactures have to develop various types of vehicles and engines to cover different demands such as fuel economy regulation and emission regulation.

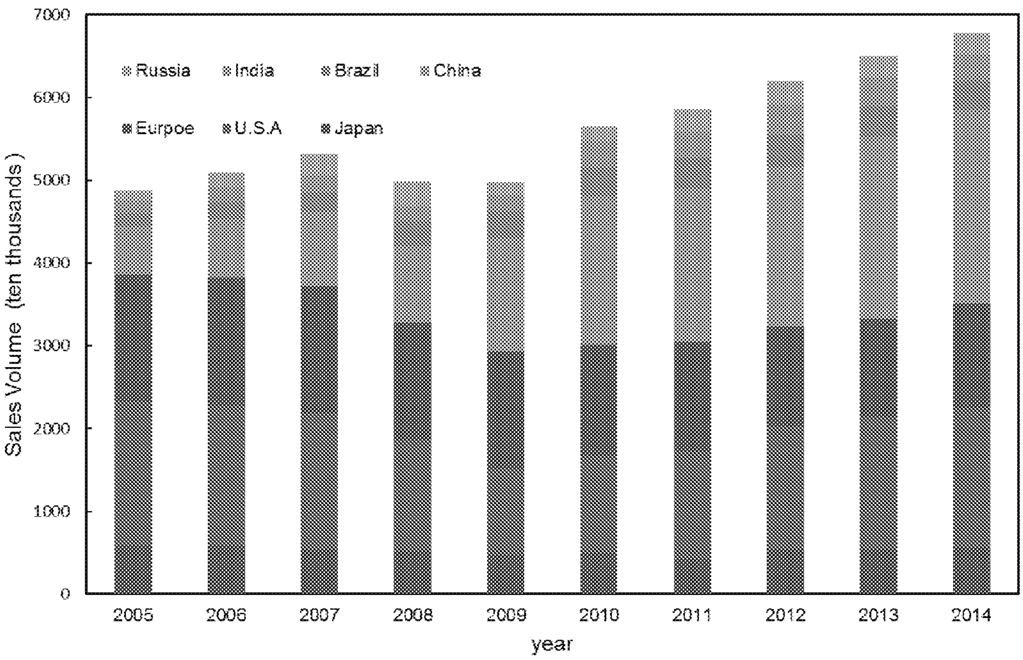

Figure 3. Sales volume in the world

Toyota supplies several types of engines for world markets. Each engine has top-level performance in each engine displacement. However, each engine has different characteristics and configurations. Figure 4 shows the examples of cross section views of Toyota's engines. As it can be seen, each engine has different configurations in the detailed part such as stroke bore ratio and valve included angle. Figure 5 shows the combustion comparison of Toyota's engines. Even though each engine has top-level performance in each category, each engine has different combustion duration. These examples mean that independent efforts, such as the combustion concept design and the engine calibration, are required for each engine development.

To supply attractive and environmental friendly vehicles to customers in the world, efficient development is essential because car manufactures have to develop various number of engines to meet the worldwide demand. However, since Toyota is always pursuing better value of product, the engine development is not always focused on only efficient development. In Toyota's engine development, yielded time by making engine developments more efficient is used to enhance the value of product. To realize this development, a new common architecture concept will be utilized in the next generation engine development. The characteristics of a new common architecture concept are not only to succeed Toyota's ESTEC technologies such as fast combustion which is realized with tumble concept and but also to pursue maximum engine specific output as shown in Figure 2.

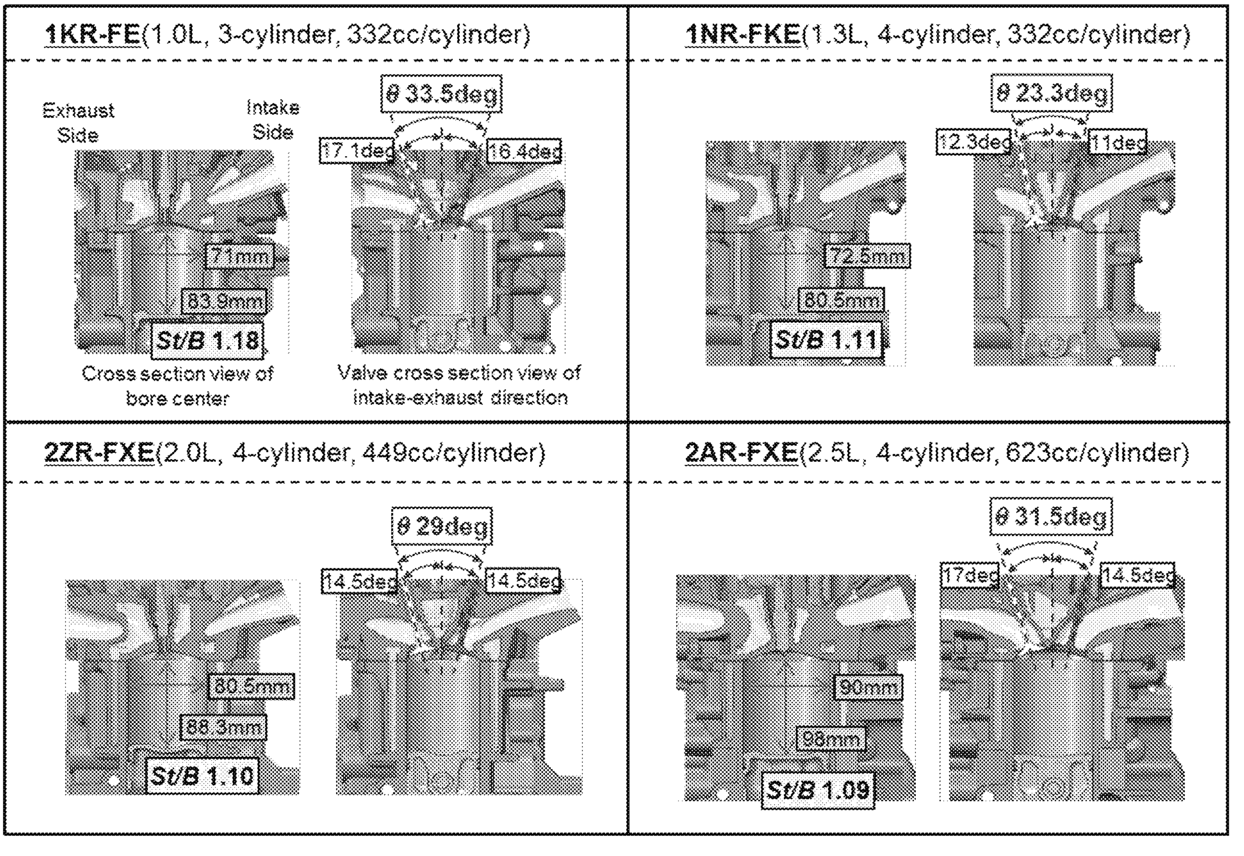

Figure 4. Engine configurations

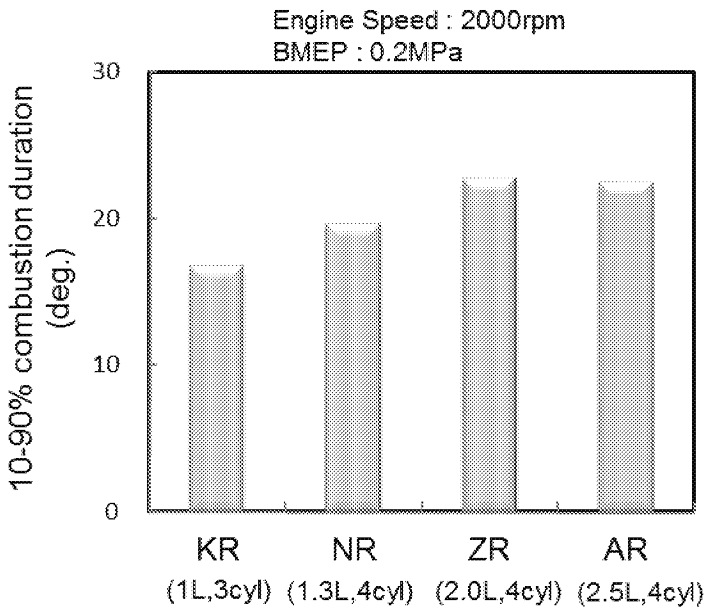

Figure 5. Combustion comparison

Combustion Characteristics

In engines, it is well known that turbulence intensity has an important role to enhance combustion and Damköler's argument has been had a strong influence on combustion research since 1940. In the past fundamental researches, some equations on turbulent burning velocity were proposed. Equation (1) is widely used equation to express turbulent burning velocity. In this equation, St, SL, and u' mean turbulent burning velocity, laminar burning velocity, and turbulence intensity respectively. This equation shows that turbulence intensity has a large role on turbulent burning velocity. Equation (2) shows one example to express laminar burning velocity with equivalence Φ, gas temperature T and pressure P [6]. In addition to these kind of equations, phase diagram of turbulent combustion is often used to describe the combustion characteristics [7].

$$\frac{S_T}{S_L} = 1 + C\left(\frac{u'}{S_L}\right)^n \qquad (1)$$

$$S_L = [30.5 - 54.9(\Phi - 1.21)]\left(\frac{T_u}{T_0}\right)^\alpha \left(\frac{p}{p_0}\right)^\beta \qquad (2)$$

Figure 6 shows the relationship between turbulence intensity and combustion characteristic which comes from in-house data. Since this figure covers lots of test engines and test conditions, detailed information about engines and test conditions is not described. In this figure, Y-axis represents that bore diameter divided by 10-90% combustion duration. Therefore, it can be considered that Y-axis gives one index to express burning velocity. As it can be seen, turbulence intensity has a strong correlation with burning velocity as the results of fundamental researches. This result shows that turbulence intensity should be in proportion to bore diameter to realize same 10-90% combustion duration. The necessity of realizing same 10-90% combustion duration is described in the next chapter. The important point is that the design of turbulence intensity in the combustion chamber leads to determine the potential of combustion. In real engine development, turbulence intensity is enhanced by tumble port in Toyota ESTEC engines. In addition to turbulence intensity, the ignition process is so important to enhance combustion. Therefore, intake airflow which determines turbulence intensity should be considered to design combustion [8, 9].

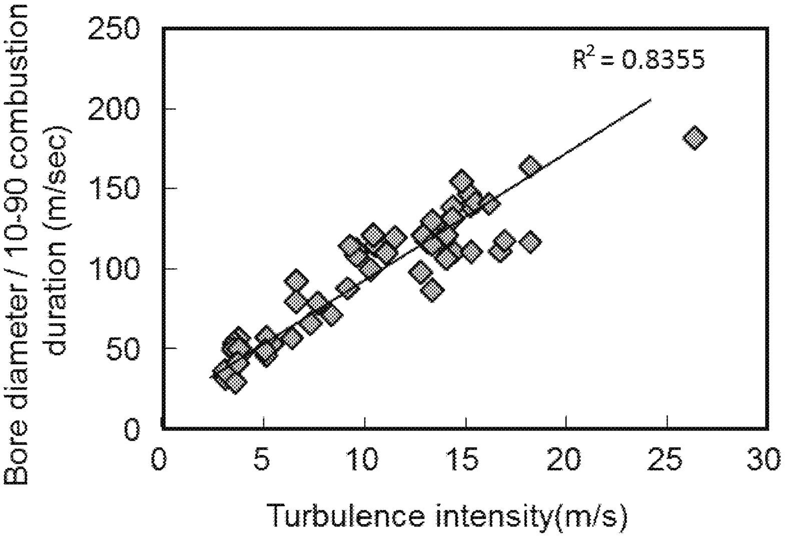

Figure 6. Relationship between turbulence intensity and combustion characteristics

Combustion Target

Fast combustion leads to expand EGR limit and enhance the engine thermal efficiency as demonstrated in ESTEC technology. Figure 7 shows the EGR limit and fuel consumption improvement in various test conditions against 10-90% combustion duration without EGR. It shows that fast combustion is desirable for lowering fuel consumption. However, premature fast combustion has some issues such as increase in cooling heat loss due to high combustion temperature, and combustion noise. Therefore, an appropriate combustion velocity should be considered.

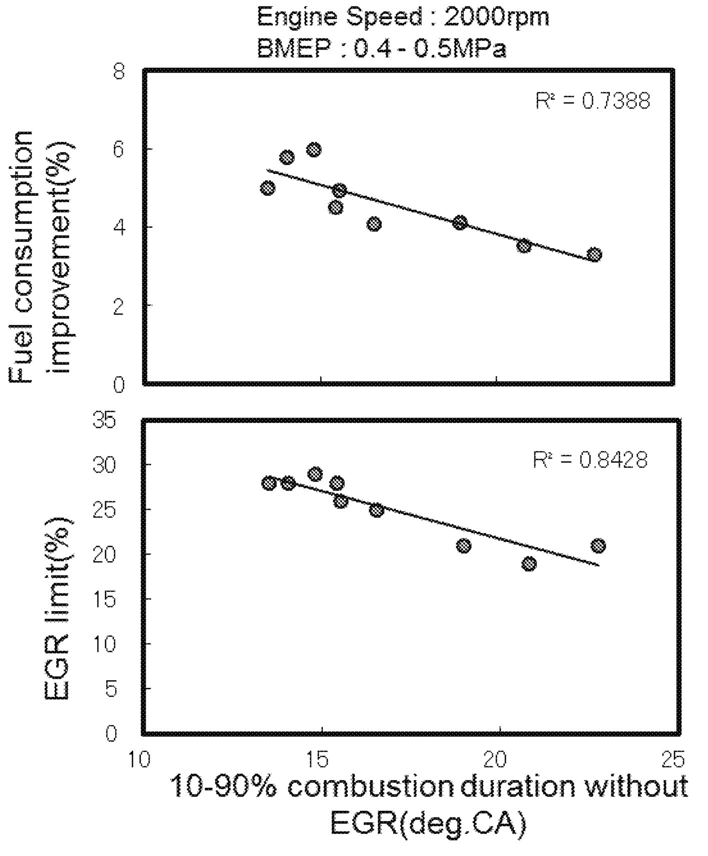

Figure 7. Relationship between 10-90% combustion duration and EGR limit

To consider the appropriate combustion duration from the viewpoint of fuel consumption, the effect of combustion duration on the engine thermal efficiency is estimated with AVL Boost. Figure 8 shows the results without EGR condition at 2000rpm and 6000rpm. In this figure, base point means the reference point of the engine thermal efficiency. As it can be seen, shorter combustion duration gives higher engine thermal efficiency under the adiabatic condition which means that cooling heat loss does not exist. However, since cooling heat loss exists in the real engines, there is a trade-off for combustion duration. In the case of 2000rpm, the appropriate combustion duration seems to be around 15 degrees of crank angle. On the other hand, the appropriate combustion duration seems to be less than 10 degrees of crank angle at 6000rpm. The difference of the appropriate combustion duration comes from the effect of cooling heat loss. Figure 9 shows the effect of combustion duration on degree of constant volume and cooling heat loss ratio when engine speed is changed. The difference of increase in cooling heat loss ratio can be seen less than 30 degrees of crank angle of 10-90% combustion duration, because the duration of heat transfer from combustion gas to cylinder wall gets long when the engine speed becomes low.

As shown in Figure 7, shorter combustion duration also has a large effect to expand EGR limit and reduction in fuel consumption. However, strengthening turbulence intensity is required to reduce combustion duration as shown in Figure 6. It means that flow coefficient of intake port decreases when high tumble concept is adopted [3]. Therefore, the effect of high tumble on engine output performance should be considered. The current engine combustion situation as shown in Figure 5 and intake port development trend show that the appropriate combustion duration is around 15-20 degrees of crank angle of 10-90% combustion duration.

This estimation indicates that the appropriate combustion duration for larger engine displacement with smaller S/V ratio becomes short. However, it seems that the difference is so small when the engine displacement changes within the range of production engines. Therefore, it can be considered that the appropriate combustion duration in this estimation can be applied to all Toyota's engines.

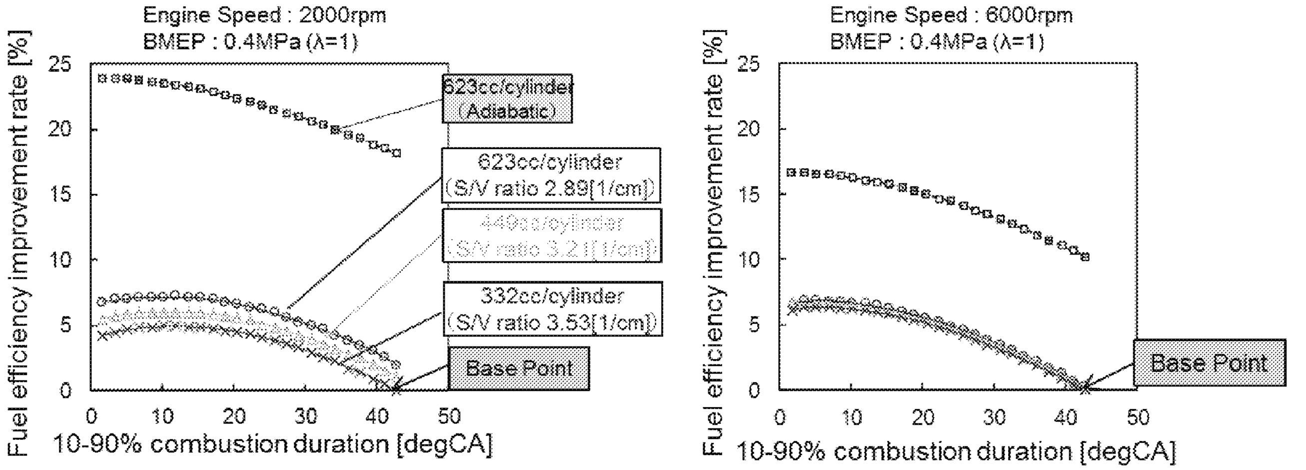

Figure 8. Effect of combustion duration on fuel efficiency

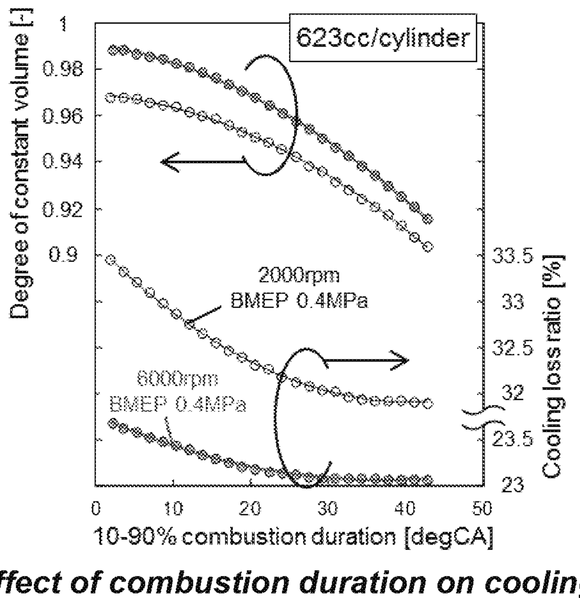

Figure 9. Effect of combustion duration on cooling heat loss

Combustion Design

Engine design should be considered lots of criteria, because engines have important dimensions which determine combustion characteristics and the engine output performance. Therefore, some assumption should be defined before considering the common architecture concept. The fundamental assumption is that stroke bore ratio is constant to consider the common architecture (S/B = constant). As for combustion characteristics, turbulence intensity should be in proportion to bore diameter to realize same 10-90% combustion duration as shown in the previous part and the method for enhancing combustion is high tumble concept.

In this part, some basic equations are described to realize almost same combustion duration in the common architecture concept. Figure 10 shows tumble flow at intake valve close timing and turbulence at TDC. Tumble ratio at intake close timing can be described by equation (3) and (4). Kinetic energy can be described by equation (5) and (6).
The tumble flow is converted to turbulence by shear force while the piston moves to TDC.

$$TR = \omega/\omega ne \qquad (3)$$
$$\omega ne = 2\pi \cdot Ne/60 \qquad (4)$$

ωne : Engine Angular Velocity
Ne : Engine Speed

$$E_{IVC} = \frac{1}{2} \cdot I\omega^2 \qquad (5)$$
$$I = a \cdot R^2 \cdot m \qquad (6)$$

I: Moment of Inertia
a : Vortex Geometry Coefficient
m : Mass

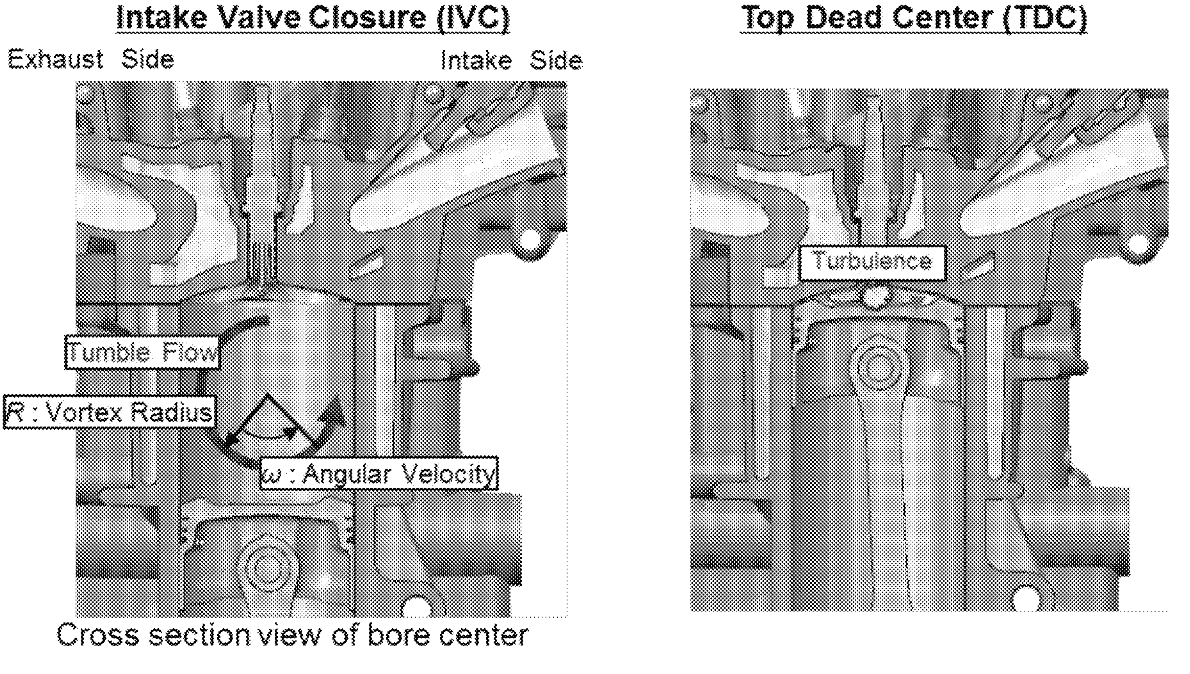

Figure 10. Engine configurations

Figure 11 shows the relationship between kinetic energy at IVC and turbulence energy at TDC. In this figure, IVC is constant when tumble ratio is changed. This relationship is estimated by using STAR-CD. The tested engines are 1.3L engine (1NR-FKE) and its similar figure engines with same S/B ratio as shown in Figure 12. The result shows that turbulence energy at TDC is almost in linear proportion to kinetic energy at IVC. Therefore, turbulent energy at TDC can be described by equation (7). Here, σ is coefficient of conversion from kinetic energy at IVC to turbulence energy at TDC.

$$k = \sigma \cdot E_{IVC} \qquad (7)$$

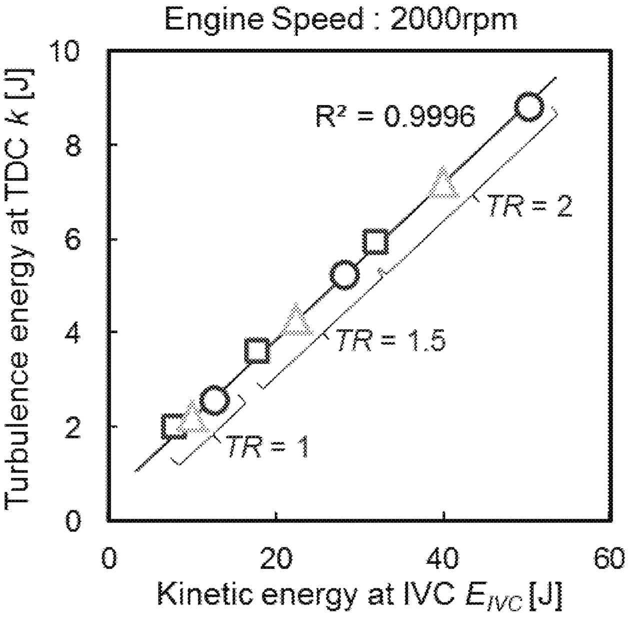

Figure 11. Relationship between kinetic energy and turbulence energy

	□	△	○
Bore [mm]	72.5	80.5	90
Stroke [mm]	80.5	89.4	99.9
Displacement [cc]	332.3	454.9	635.7
St/B [-]		1.11	

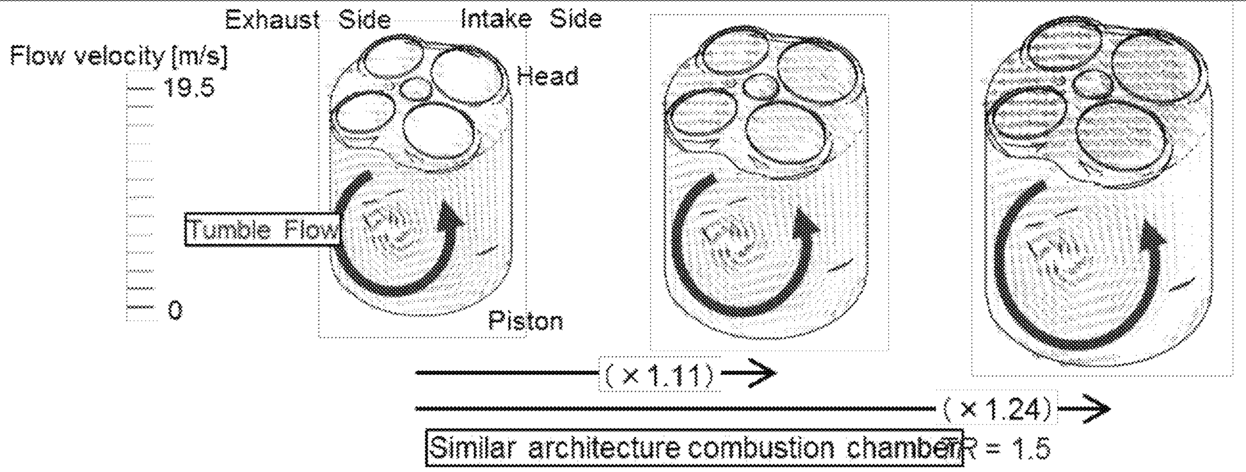

Figure 12. Assumption in CFD model

Turbulence energy also can be described by equation (8). This equation is based on the standard CFD model. In this equation, u' means turbulence intensity.

$$k = \frac{3}{2} \cdot m \cdot u'^2 \qquad (8)$$

Therefore, u' can be described by equation (9). In this equation, vortex radius R is proportional to bore diameter B and $2\pi \cdot Ne \cdot \sqrt{\frac{\sigma \cdot a}{3}}$ can be considered almost constant because stroke bore ratio is constant in this case. It means that u' is proportional to $TR \cdot B$ as shown in equation (10). These equations mean that TR should be constant to realize same 10-90% combustion duration under the assumption that stroke bore ratio is constant. This consideration is very essential for the intake port design.

$$u' = \sqrt{\frac{2k}{3m}}$$

$$= \sqrt{\frac{2\sigma \cdot E_{IVC}}{3m}}$$

$$= TR \cdot R \cdot 2\pi \cdot Ne/60 \cdot \sqrt{\frac{\sigma \cdot a}{3}} \qquad (9)$$

$$u' \propto TR \cdot B \qquad (10)$$

In the next part, the philosophy to fix up the primal parameters such as intake port diameter, intake valve diameter, and intake valve lift is mentioned for realizing same 10-90% combustion duration. Figure 13 shows the important dimensions.

As for intake port diameter and intake valve diameter, the standard assumption is that these dimensions are proportional to bore diameter as shown in equations (11) and (12). The requirement of intake valve lift is derived from the assumption of equations (11) and (12).

$$d_{port} \propto B \qquad (11)$$

$$d_{valve} \propto B \qquad (12)$$

Tumble ratio can be described by equation (13) by using equation (3) and (4). In this equation, tumble ratio TR is expressed by angular velocity ω which is determined with some fundamental factors. Here, some important characteristics are expressed.

$$TR \propto \omega \qquad (13)$$

To consider angular velocity ω, the effect of intake port flow rate, intake valve flow rate, and in-cylinder flow rate should be considered. Since the movement of piston generates air flow in the engine, piston speed is a key factor to determine air flow and turbulence intensity. Piston speed is in proportion to stroke and bore diameter as shown in equation (14), because stroke bore ratio is constant. Since intake port flow rate is in proportion to piston speed, intake port flow rate turns out to be in proportion to bore diameter as shown in equation (15). Intake valve flow rate has a correlation between intake port area and vale curtain area. Therefore, intake valve flow rate can be described by equation (16) and in-cylinder flow rate is calculated by equation (17). Angular velocity is presented by equation (18) and as a result, tumble ratio is described by equation (19) using the relationship between equation (13) and (18). Since the important consideration is that TR is constant and intake valve diameter is in proportion to bore diameter, the requirement of intake valve lift is to be proportional to bore diameter as shown in equation (20).

$$V_{piston} \propto S \propto B \qquad (14)$$

$$\begin{aligned} u_{port} &\propto V_{piston} \\ &\propto B \end{aligned} \qquad (15)$$

$$\begin{aligned} u_{valve} &\propto u_{port} \cdot \frac{\pi \cdot d_{port}^2/4}{\pi \cdot d_{valve} \cdot L} \\ &\propto \frac{B^3}{d_{valve} \cdot L} \end{aligned} \qquad (16)$$

$$\begin{aligned} u_{in-cylinder} &\propto u_{valve} \\ &\propto \frac{B^3}{d_{valve} \cdot L} \end{aligned} \qquad (17)$$

$$\begin{aligned} \omega &= 2\pi \cdot \frac{u_{in-cylinder}}{c} \\ &\propto \frac{B^3}{d_{valve} \cdot L \cdot c} \\ &\propto \frac{B^2}{d_{valve} \cdot L} \end{aligned} \qquad (18)$$

$$TR \propto \frac{B^2}{d_{valve} \cdot L} \qquad (19)$$

$$L \propto B \qquad (20)$$

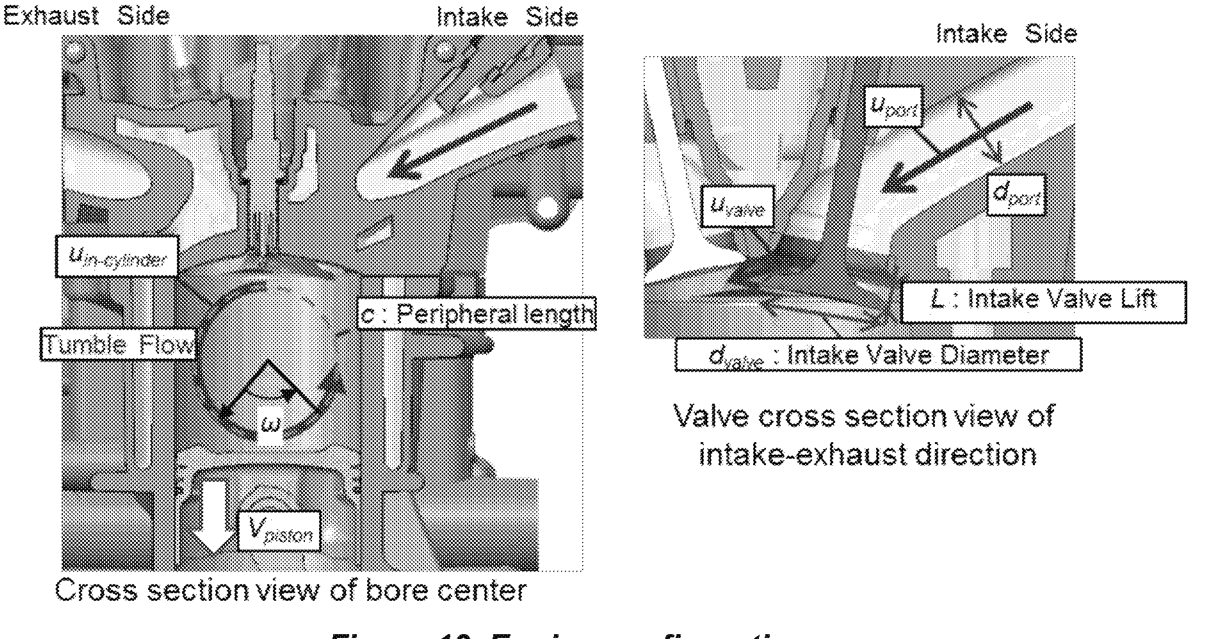

Figure 13. Engine configurations

To consider the intake valve lift dimension, the relationship between the combustion characteristics and the engine output performance should be understood, because it is common sense that high intake valve lift contributes to increasing intake air volume under high engine speed area which leads to high engine output performance. Figure 14 shows an example of relationship between intake valve lift and tumble ratio with 1.3L engine. As it can be seen, higher intake valve lift gives higher tumble ratio. However, the effect on enhancing tumble ratio becomes small even though intake valve lift is enlarged more than 10mm. Figure 15 shows the effect of intake valve lift on turbulence intensity and volumetric efficiency, which is estimated by CFD. This result also shows higher intake valve lift gives higher volumetric efficiency which leads to higher engine output performance and saturates turbulence intensity around 10mm of intake valve lift. This result indicates that it is possible to make an engine design which is compatible with same combustion duration and high engine output performance.

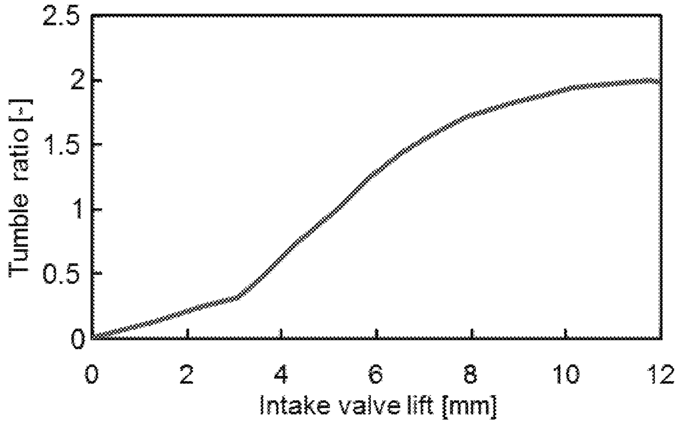

Figure 14. Relationship between intake valve lift and tumble ratio

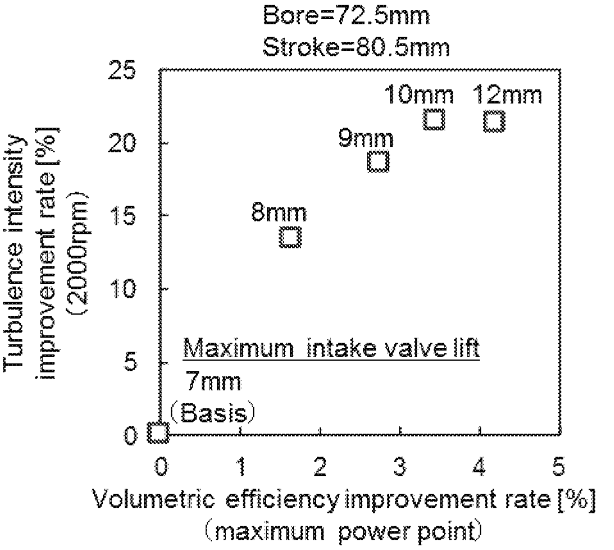

Figure 15. Effect of intake valve lift on turbulence intensity and volumetric efficiency

Results and discussion

To verify the discussion in the previous section, some engine tests are conducted by changing intake port design of Toyota's production engines. Engines used for this verification are 1.3L engine, 2.0L engine, and 2.5L engine, because these engines have similar stroke bore ratio as shown in figure 4. Figure 16 shows the effect of tumble ratio on combustion duration for those three engines. As it can be seen, higher tumble ratio gives shorter combustion duration which leads to higher thermal efficiency. This is the reason why higher tumble ratio concept has been adopted in Toyota's ESTEC engines. This figure also shows that same 10-90% combustion duration is achieved by similar TR for all three engines. Therefore, the important philosophy on tumble ratio design is established for the new common architecture concept. It means that similar tumble ratio design leads to similar 10-90% combustion duration in the condition of same stroke bore ratio and Toyota's engine will have similar tumble ratio against for similar stroke bore ratio engines.

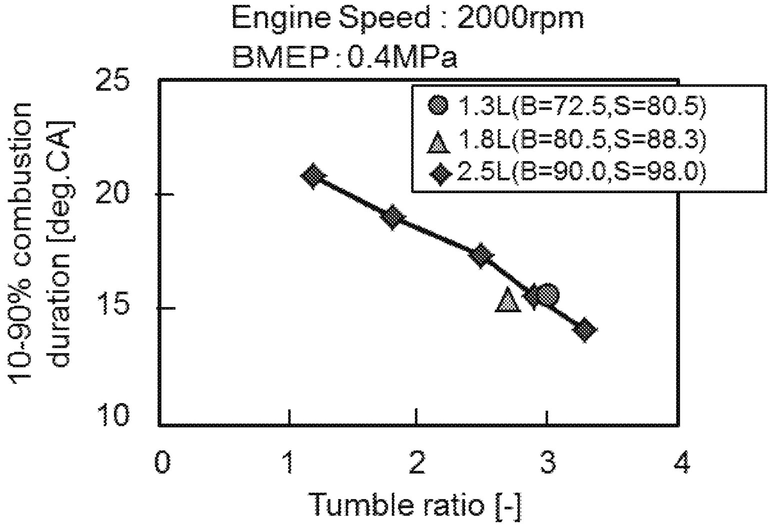

Figure 16. Effect of tumble ratio on combustion duration

Toyota's new common architecture concept improves not only combustion efficiency but also engine output performance where valvetrain system has a key role. To demonstrate the importance of valvetrain system, an analysis is made on valve included angle.

To make a tumble flow in the combustion chamber, a portion of piston movement energy is consumed as pressure drop along intake flow route from intake port to combustion chamber. Figure 17 shows an example of static pressure drop. Since the pressure drop is influenced by valve included angle, the appropriate angle is examined by CFD.

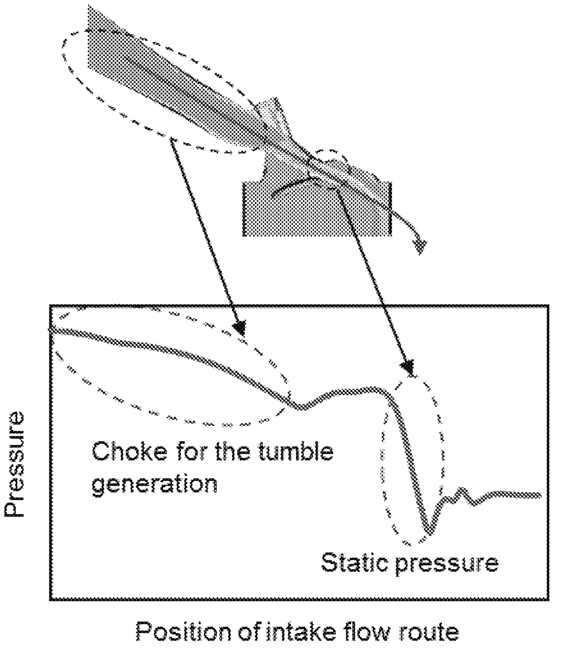

Figure 17. Static pressure drop along the intake flow route

Figure 18 shows the contour figure of tumble flow generation efficiency of tumble ratio 2.0, which is defined in equation (21). E_{IVC} is defined in equation (5) and W_{TG} is the piston work which is consumed to make tumble flow. It seems that more than 40 degrees of valve included angle gives good value. Since there is engine design limitation in the production engine development. it can be considered that around 40 degrees of valve included angle is a comfortable angle regarding the engine design. To verify this estimation, the engine head is prototyped. The valve included angle with the angle between intake port and intake valve is plotted as a red point.

$$\eta = \frac{E_{IVC}}{W_{TG}} \qquad (21)$$

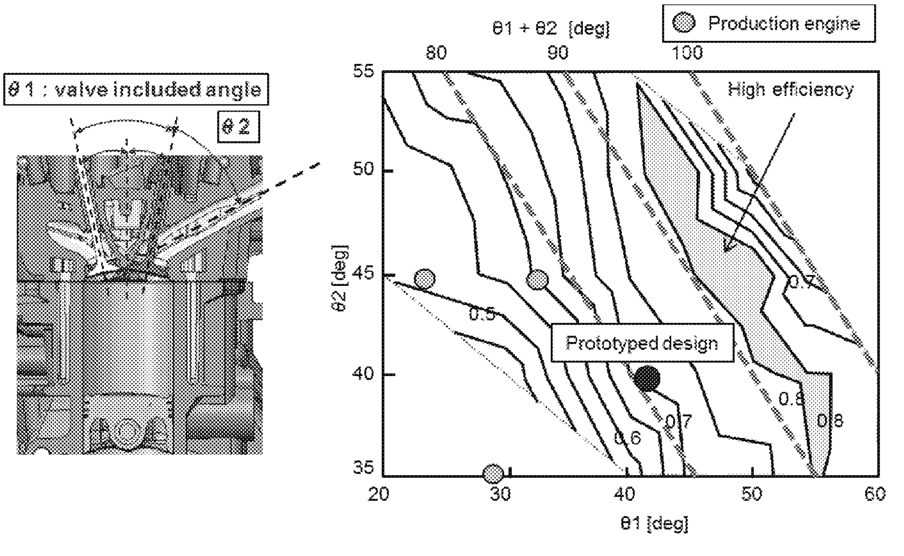

Figure 18. Effect of valve included angle on tumble flow generation efficiency

The left side of Figure 19 shows the prototyped design and the right side shows the measurement result on tumble ratio and flow coefficient. As it can be seen, better performance is achieved by changing the layout of the valve included angle and the intake port.

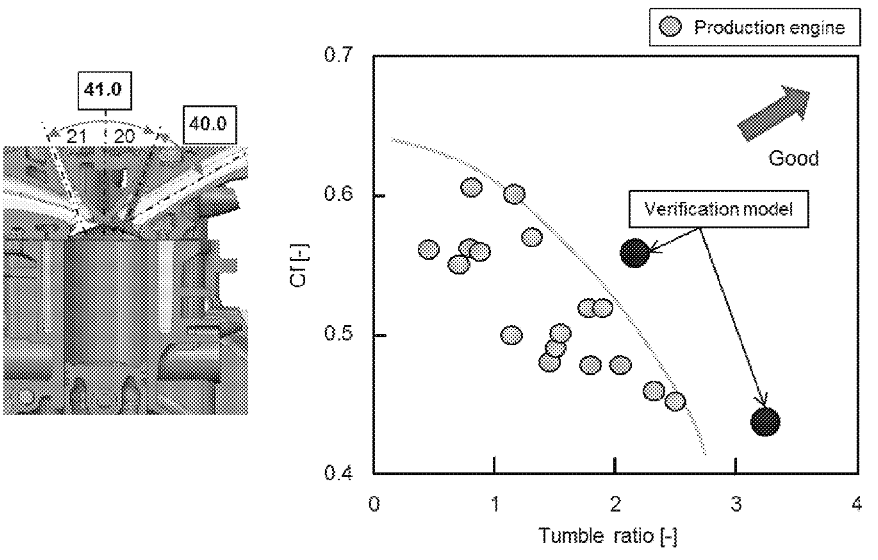

Figure 19. Effect of valve included angle on tumble ratio and flow coefficient

The layout of valvetrain system is identified as an important parameter for Toyota's new common architecture concept to realize both high engine thermal efficiency and high engine output.

Conclusion

Improving both the engine thermal efficiency and the output performance is essential to meet the environmental requirements and to realize customer's smile. For this purpose, Toyota is challenging to build up a new common architecture concept. The key point is to realize same combustion duration for different engine series with high engine output performance. In this paper, fundamental guideline is presented for next generation engine developments. The fundamental assumption is that stroke bore ratio is constant when the engine displacement changes.

1) To build up the fundamental guideline for a new common architecture, some basic equations and CFD analysis are discussed. For achieving same combustion duration, turbulence intensity should be proportional to bore diameter. Therefore, tumble ratio should be constant even if the engine displacement is different.
2) To verify the fundamental guideline, some engine tests are conducted. Since same 10-90% combustion duration is achieved for all engines when similar tumble ratio is kept same, fundamental guideline of tumble concept can be applied to the engine design process.
3) Main dimensions such as intake port diameter and intake valve diameter are also proposed to be proportional to bore diameter. As for intake valve lift quantity, larger valve lift is in the favour of the engine output performance.

4) To realize both high engine thermal efficiency and high engine output, the layout of the valve included angle and the intake port plays an important role.
5) Toyota's new common architecture concept will cover the new guideline described in this conclusion part. It can be expected to decrease engine calibration time, because new engines will have similar dimensions and an engine calibration of one engine can be applied to other engines.

Toyota's new generation engines will make a major breakthrough with a new common architecture concept. With new generation engines, Toyota will contribute to improve environmental issues and realize customer's smile.

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